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W and Z Physics at CDF

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Abstract

We present recent measurements of W and Z-boson physics using data collected by CDF experiment at run II of the Fermilab Tevatron collider.

1 Introduction

Run II of the Fermilab Tevatron presents us with a unique opportunity to study W and Z boson physics. Compared to the LEP and SLD accelerators, where many of the best measurements of the electroweak parameters have been made to date, the Fermilab Tevatron has three unique advantages:

- The Tevatron produces a large flux of W bosons.
- The Tevatron is able to produce Z/γ^* bosons at high masses.
- As the colliding particles are protons and anti-protons, the W and Z bosons produced are particularly sensitive to up and down quarks.

These unique features, along with new subdetectors in the forward regions, allow the Tevatron experiments to probe a wide range of electroweak physics. Among the topics to be explored at the Tevatron electroweak programme are:

- Cross sections for W and Z boson production; preliminary results from CDF run II will be presented later in this talk.
- Direct and indirect measurements of the W boson width; a preliminary result for the indirect measurement of the W width will also be presented here.

- Lepton universality in W and Z decays.
- Asymmetries in the production of W and Z bosons. These are sensitive to $\sin^2(\theta_W)$ and the u and d quark couplings.
- The W boson mass.
- Di-boson production cross sections, which can be used to measure tri-boson couplings. Preliminary results for some di-boson cross sections will be presented in this talk.

Many of these results can be used to look for physics beyond the Standard Model; for example: unexpected tri-boson couplings, Z' resonances and anomalous quark couplings. We will also use our results to update the constraints on the Standard Model Higgs boson mass.

As of this conference, the Fermilab Tevatron has delivered about 430 pb^{-1} of integrated luminosity, of which CDF has recorded around 350 pb^{-1} to tape. The analyses presented in this talk use around 72 pb^{-1}, 120 pb^{-1} or 200 pb^{-1} of integrated luminosity. The uncertainty on the integrated luminosity measurements is $\pm 6\%$, coming from two roughly equal components: the uncertainty on the inelastic $p\overline{p} \rightarrow p\overline{p}$ cross section at 1.96 TeV and our knowledge of the acceptance of the luminosity monitors.

All of the results presented at this conference are preliminary. After this conference, CDF has published results on the inclusive W and Z boson cross section and related quantities[1].

2 The CDF Run II Detector

To describe the position of a signal in the detector we use two coordinates: the azimuthal angle (ϕ) and the pseudo-rapidity (η). The pseudo-rapidity, η, is defined in terms of θ, the polar angle between the proton beam direction and the detector, as:

$$\eta \equiv -\log(\theta/2) \tag{1}$$

To reconstruct the signals presented in this talk we primarily use 4 subdetectors: the central tracking detector (COT), the central and forward calorimeters, and the muon systems. The COT is placed inside a 1.4 T magnetic field and is used to reconstruct tracks from charged particles in the region $|\eta| < 1$. The central calorimeter covers the region $|\eta| < 1$ and the forward, or 'plug', calorimeters cover the region $1 < |\eta| < 3.6$. The calorimeters measure both electromagnetic and hadronic energy. Clusters of energy in the central electromagnetic calorimeter are used to reconstruct electrons - which are required to match to a COT track - and photons - which are required to have no matching track. A second class of electrons is reconstructed using the plug electromagnetic calorimeters, without any track requirement. The muon systems cover the region $|\eta| < 1.5$. Muons are reconstructed by matching COT tracks to hits in the muon chambers.

Neutrinos may be partially reconstructed by exploiting two features of the CDF experiment: the detector is almost hermetic perpendicular to the beam, and the constituent partons of the protons and anti-protons carry almost no momentum transverse to beam. This means the energy in the event must balance in the transverse direction. Neutrinos do not interact in the detector, resulting in an energy imbalance, or "missing-E_T" signature ($\not\!\!E_T$), from which we determine the transverse direction ($\phi(\nu)$) and transverse component of the energy ($E_T(\nu)$) carried away by the neutrino.

3 W and Z signals

Due to the clean signature, and relatively high branching fraction, we look for W and Z boson signals by reconstructing their decays into leptons. For these measurements we use 72 pb^{-1} of integrated luminosity.

3.1 Inclusive W cross section

For the measurement of the inclusive $p\overline{p} \to W$ cross section at $\sqrt{s} = 1.96$ TeV we look for $W \to \mu\nu$ and $W \to e\nu$ signals. In the detector we look for for one muon, or one central electron with high momentum transverse to the beam, $p_T(\mu) > 20$ GeV/c, $p_T(e) > 25$ GeV/c, plus a large missing-E_T signal, $\not\!\!E_T > 20$ GeV (in the μ channel) or $\not\!\!E_T > 25$ GeV (in the e channel).

As we do not know the longitudinal component of the neutrino's momentum, we cannot fully reconstruct the mass of the W-boson. Instead we define the 'transverse mass' (m_T) of the lepton and the neutrino using only the transverse components of the momentum as follows:

$$m_T = \sqrt{E_T(\ell) \cdot E_T(\nu) \cdot (1 - \cos(\Delta\phi(\nu, \ell)))} \tag{2}$$

where $\Delta\phi(\nu, \ell)$ is the polar angle between the measured lepton and the inferred position of the neutrino. Figure 1 shows the transverse mass for the $W \to \mu\nu$ candidate events.

Backgrounds to the W signal come from QCD processes, $Z \to \ell^+\ell^-$ decays (where one of the leptons is not detected), $W \to \tau\nu$ decays and cosmic rays (in the muon channel). Table 1 shows the number of events, background estimate and acceptance

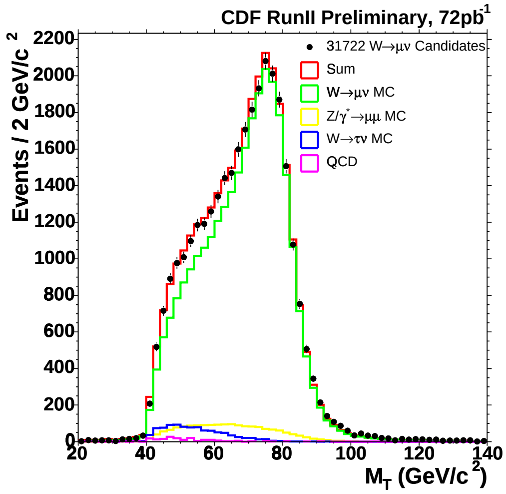

Figure 1: *The transverse mass (m_T) for $W \to \mu\nu$ candidate events. The distributions from a Monte Carlo (MC) simulation of the signal and backgrounds are also shown.*

$\times$ efficiency for the two signals. The measured cross section times branching ratios are:

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to W \to \mu\nu) = 2772 \pm 16 \,^{+64}_{-60} \pm 166 \text{ pb} \quad (3)$$

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to W \to e\nu) = 2782 \pm 14 \,^{+61}_{-56} \pm 167 \text{ pb} \quad (4)$$

where the first uncertainty is due to the statistics of the candidate events; the second uncertainty is from systematic effects; and the third is due to the uncertainty on the luminosity measurement.

3.2 Inclusive Z cross section

We measure the cross section times branching ratio of $p\overline{p} \to Z$ at $\sqrt{s} = 1.96$ TeV using electrons and muon final states.

For $Z \to e^+e^-$ decays, we take advantage of the new forward calorimeters installed for run II. We look for $Z \to e^+e^-$ events where one electron is reconstructed in the central calorimeter, and the second electron is reconstructed either in the central calorimeter (the CC sample), or in the new plug (forward) calorimeter (the CP sample). The addition of the CP sample more-than-doubles the number of $Z \to e^+e^-$ candidate events found. For $Z \to \mu^+\mu^-$ events we look for one central muon, plus one other track. The numbers of candidate events found and the acceptance times efficiency for the two signals is given in table 2. Backgrounds come from QCD processes in which a jet is mis-reconstructed as a lepton, W and Z decays into taus and from cosmics (in

Candidate events in 72 pb^{-1}		estimated background	acceptance $\times$ efficiency
$W \to \mu\nu$	31,772	$(10.6 \pm 0.4)\%$	$(17.94^{+0.36}_{-0.33})\%$
$W \to e\nu$	37,574	$(4.4 \pm 0.8)\%$	$(14.39^{+0.32}_{-0.31})\%$

Table 1: *Number of $W \to \ell\nu$ candidate events, estimated background and acceptance times efficiency for the two channels.*

Candidate events in 72 pb^{-1}		acceptance $\times$ efficiency
$Z \to e^+e^-(\mathrm{CC})$	1730	$(22.74^{+0.47}_{-0.48})\%$
$Z \to e^+e^-(\mathrm{CP})$	2512	
$Z \to \mu^+\mu^-$	1785	$(10.18^{+0.24}_{-0.28})\%$

Table 2: *Number of $Z \to \ell^+\ell^-$ candidate events and acceptance times efficiency for the three channels.*

the muon channel). All of the backgrounds are small, totaling less than 1.5%. The results for the cross section times the branching ratio for $66 < m(\ell^+\ell^-)/\mathrm{GeVc}^{-2} < 116$ is:

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to Z/\gamma^* \to e^+e^-) = 255.2 \pm 3.9 \,^{+5.5}_{-5.4} \pm 15.3 \text{ pb} \quad (5)$$

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to Z/\gamma^* \to \mu^+\mu^-) = 248.9 \pm 5.9 \,^{+7.0}_{-6.2} \pm 14.9 \text{ pb} \quad (6)$$

The first uncertainty is due to the statistics of the candidate events; the second uncertainty is from systematic effects; and the third uncertainty is from the luminosity measurement.

3.3 τ signal

CDF has also looked for W and Z signals using the tau decay mode, by reconstructing hadronic decays of taus. The signature of such a tau decay is a narrow, isolated jet with low track multiplicity. In addition the invariant mass of the tracks and π^0s in the jet must be smaller that the τ mass. 2345 $W \to \tau\nu$ candidate events are found, from which we extract a measurement of:

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to W \to \tau\nu) = 2.62 \pm 0.07 \pm 0.21 \pm 0.16 \text{ nb} \quad (7)$$

where the first uncertainty is due to the number of candidate events, the second is from systematic effects, and the third is due to the uncertainty on the luminosity measurement.

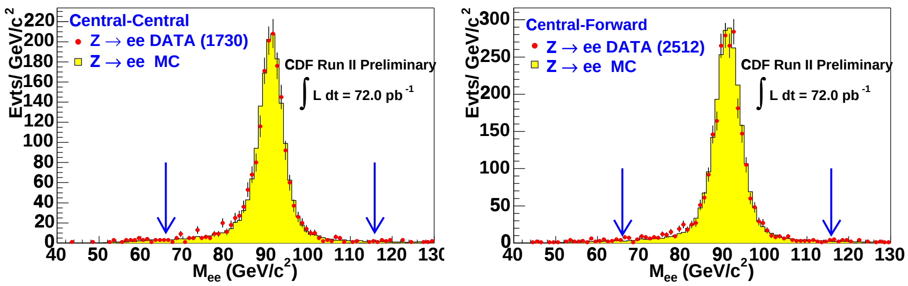

Figure 2: *Invariant mass of* e^+e^- *pairs for the central-central (CC) and central-plug (CP) samples. We use events with invariant masses between* 66 GeV/c^2 *and* 116 GeV/c^2.

3.4 Combined W and Z cross sections

Assuming lepton universality, we may combine the cross section results in the electron and muon channels, taking into account any correlated systematic effects. In the Z/γ^* channel we also make a correction for the Drell-Yan process to obtain a result for the pure Z cross section. The results we obtain for the cross section times branching ratio are:

$$\sigma \cdot BR(p\bar{p} \to W \to \ell\nu) = 2777 \pm 10 \pm 52 \pm 167 \text{ pb} \quad (8)$$

$$\sigma \cdot BR(p\bar{p} \to Z \to \ell^+\ell^-) = 254.3 \pm 3.3 \pm 4.3 \pm 15.3 \text{ pb} \quad (9)$$

As above, the first uncertainty is statistical, the second systematic and the third from luminosity.

3.5 Extracting physical quantities

We define the ratio R of the W and Z cross sections as:

$$R = \frac{\sigma \cdot \mathrm{BR}(p\bar{p} \to W \to \ell\nu)}{\sigma \cdot \mathrm{BR}(p\bar{p} \to Z \to \ell^+\ell^-)} \quad (10)$$

Many uncertainties cancel in this ratio, including the large uncertainty on the luminosity. Combining the results above, and taking into account correlated systematic effects, we obtain:

$$R = 10.93 \pm 0.15(stat) \pm 0.13(sys) \quad (11)$$

The ratio R may also be written as follows:

$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \cdot \frac{\Gamma(Z)}{\Gamma(Z \to \ell\ell)} \cdot \frac{\Gamma(W \to \ell\nu)}{\Gamma(W)} \quad (12)$$

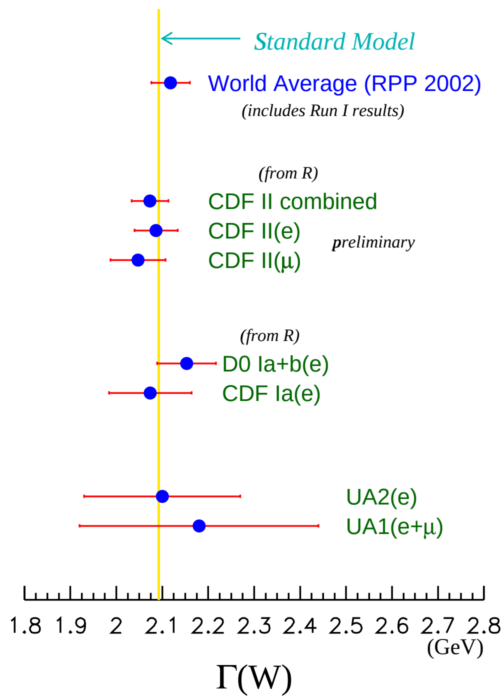

Figure 3: *Measurements of $\Gamma(W)$, compared with the world average measurement taken from[2]. The yellow band indicates the Standard Model prediction.*

Using a NNLO prediction for the ratio of the W to Z production cross sections of 3.367 ± 0.024 and the measured value for $\mathrm{BR}(Z \to \ell^+\ell^-)$ of $(3.366 \pm 0.002)\%$ from LEP[2], we extract the value for the branching ratio of the W boson into an individual lepton species to be:

$$\mathrm{BR}(W \to \ell\nu) = 0.1093 \pm 0.0021 \tag{13}$$

The partial width for $W \to \ell\nu$ is calculated (at NNLO) to be 226.4 ± 0.4 MeV[2]. We can therefore extract a value for the W-boson width of:

$$\Gamma(W) = 2071 \pm 41 \text{ MeV} \tag{14}$$

This results is compatible with, and more accurate than, the current world average of 2092 ± 42 MeV[2]. Our result is shown in figure 3, along with other measurements of $\Gamma(W)$ and the Standard Model prediction.

We also use the measured cross sections to extract results on lepton universality. Using separate R values from the electron and muon channels we obtain:

$$U = \frac{R_\mu}{R_e} = \frac{g_\mu^2}{g_e^2} = 1.022 \pm 0.036 \tag{15}$$

from which we extract:

$$\frac{g_\mu}{g_e} = 1.011 \pm 0.018 \tag{16}$$

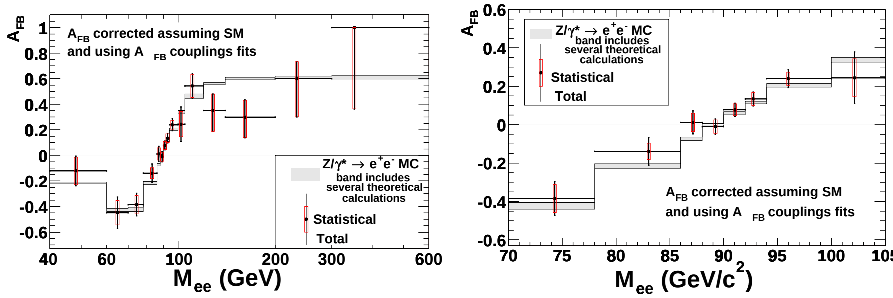

Figure 4: *The forward backward asymmetry measured in $Z \rightarrow e^+e^-$ events. The plot on the left shows the entire mass range; the plot on the right shows an enlargement of the region around the Z mass. The grey band shows the Standard Model prediction.*

which is consistent with the Standard Model.

Using data taken with trigger designed for τ-leptons, we have also extracted a result for the ratio of the couplings of the electroweak bosons to electrons and taus:

$$\frac{g_\tau}{g_e} = 0.99 \pm 0.02(stat) \pm 0.04(sys) \tag{17}$$

which is again consistent with the Standard Model.

3.6 $Z \rightarrow e^+e^-$ forward–backward asymmetry

The forward–backward asymmetry is defined in terms of the angle (θ) between the incoming proton and the outgoing electron:

$$A_{fb} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma(\cos\theta > 0) + \sigma(\cos\theta < 0)} \tag{18}$$

Figure 4 shows the measured asymmetry using 72 pb^{-1} of data together with the SM prediction. No deviation between the Standard Model and data is observed. The shape of the A_{fb} spectrum is sensitive to $\sin^2(\theta_W)$ and the u and d quark couplings to the Z-boson. In the future, CDF will use this measurement to extract values for these quantities.

4 Di-boson signals

We have used the CDF run II data to look for di-boson signals, such as $W\gamma$, $Z\gamma$ and W^+W^-. We report some preliminary results here.

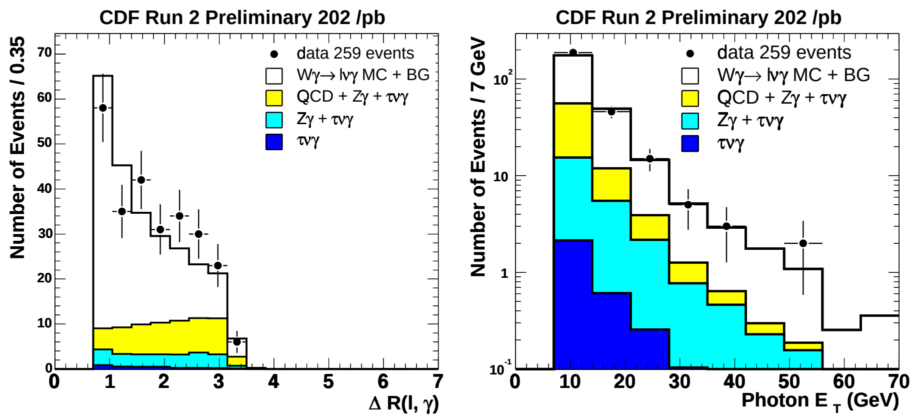

Figure 5: *Left:* $\Delta R(\ell, \gamma)$ *between the lepton and the photon. Right:* E_T *of the photon. The black points are the data. The expected backgrounds and prediction from MC are also shown.*

Candidate Events in 202 pb^{-1}		estimated backgrounds
$W\gamma \to e\nu\gamma$	131	$(25 \pm 6)\%$
$W\gamma \to \mu\nu\gamma$	128	$(32 \pm 5)\%$

Candidate Events in $\sim$ 200 pb^{-1}	
$Z\gamma \to ee\gamma$	34
$Z\gamma \to \mu\mu\gamma$	35

Table 3: *Numbers of* $W\gamma$ *and* $Z\gamma$ *event candidates, estimated backgrounds and acceptance* $\times$ *efficiency used in the calculation of the cross section.*

Di-boson signals, such as these presented here, probe the self-coupling of the electroweak bosons, as well as potential sources of non-Standard Model physics. For $W\gamma$ and $Z\gamma$ we use 202 pb^{-1} of data and look for signals with electrons or muons in the final state.

For $W\gamma \to \ell\nu\gamma$ we search for one high-p_T lepton, one photon and large $\not\!\!E_T$. Figure 5 shows the distribution of the photon E_T and the distance ($R = \sqrt{\phi^2 + \eta^2}$) between the lepton and the photon. The main backgrounds come from QCD processes and $Z\gamma$ events. For $E_T(\gamma) > 7$ GeV, $\Delta R(\ell, \gamma) > 0.7$ the cross section times branching ratio is measured to be:

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to W\gamma \to \ell\nu\gamma) = 19.7 \pm 1.7(stat) \pm 2.0(sys) \pm 1.2(lum)\ \mathrm{pb} \tag{19}$$

Using the same kinematic cuts, a leading-order calculation with $E_T(\gamma)$-dependent k-factors predicts a cross section times branching ratio of 19.3 ± 1.3 pb[3].

For $Z\gamma$ signals we look for two oppositely charged leptons and one photon. Backgrounds come from jets that are mis-reconstructed as photons and are estimated to

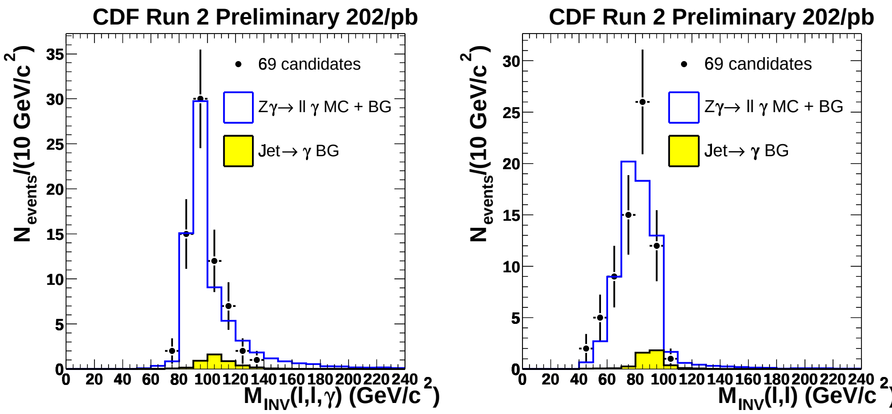

Figure 6: *Left: invariant mass of the two leptons and the photons in $Z\gamma$ candidate events. Right: The invariant mass of the two leptons. The blue lines show the prediction from MC, and the yellow histograms show the predicted background from jets which fake a lepton signal.*

be less than 10%. Again, for $E_T(\gamma) > 7$ GeV, $\Delta R(\ell,\gamma) > 0.7$ we measure:

$$\sigma \cdot \mathrm{BR}(p\overline{p} \to Z\gamma \to \ell\nu\gamma) = 5.2 \pm 0.6(stat) \pm 0.4(sys) \pm 0.3(lum) \text{ pb} \tag{20}$$

A next-to-leading order calculation, for the same kinematic cuts, predicts 5.4 ± 0.4 pb[3]. Figure 6 shows the invariant mass of the two leptons and of the lepton-lepton-photon system.

To search for W^+W^- events we use 126 pb^{-1} of CDF run II data and again exploit the large W branching ratio into electrons and muons. We look for two oppositely charged high-p_T muons and/or central electrons and large $\not{E}_T$. To minimize backgrounds, event with jets, or events where the two leptons are the same flavour and have an invariant mass close to the Z-mass ($76 < m(\ell^+\ell^-)/\mathrm{GeVc}^{-2} < 106$), are rejected. Figure 7 shows the distribution of $\not{E}_T$ versus $\Delta\phi(\nu,\ell)$. Five candidate events are found; (2.3 ± 0.4) of them are expected to be remaining background from Drell-Yan, QCD processes, and WZ and $t\overline{t}$ production. Using these events the measured cross section is:

$$\sigma(p\overline{p} \to W^+W^-) = 5.1^{+5.4}_{-3.6}(stat) \pm 1.3(sys) \pm 0.3(lum) \text{ pb} \tag{21}$$

This may be compared to a NLO prediction of $\sigma(p\overline{p} \to W^+W^-) = 12.5 \pm 0.8$ pb[4].

5 Conclusions and Future Prospects

CDF has measured inclusive W and Z cross section using electron, muon and tau channels. From these we have extracted results on lepton universality and an indi-

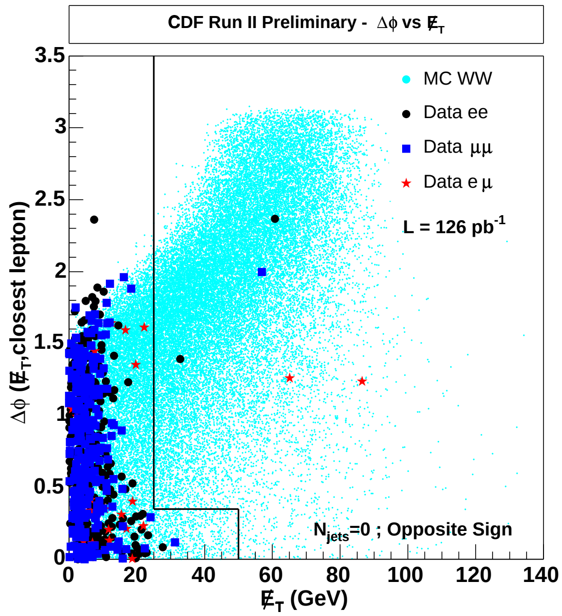

Figure 7: *The azimuthal angle difference between the lepton missing-E_T versus the magnitude of the missing-E_T in W^+W^- candidate events. The line represents the cut value.*

rect measurement of the W-boson width. We have looked at the forward–backward asymmetry in $Z \to e^+e^-$ decays. CDF has also measured di-boson cross sections for the $W\gamma$, $Z\gamma$ and W^+W^- processes. All of the measurements agree with the Standard Model predictions.

We have much more data on tape; we look forward to continue to test the Standard Model predictions for W and Z bosons and look for any hint of new physics.

6 Acknowledgments

I would like to thank the organisers for a wonderful conference and my CDF colleagues for their hard work and their input to this talk.

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